ADMINISTRATIVE INFORMATION

1. **Project Name:** ***Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance***

2. **Lead Organization:** Oak Ridge National Laboratory
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Oak Ridge, TN 37831

3. **Principal Investigator:** Gerard M. Ludtka
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4. **Project Partners:** **Cummins Inc** (technical collaboration and specimen fabrication support),
Roger D. England
Florida State University
National High Magnetic Field Laboratory (technical collaboration and facilities/experimental support including an ORISE Summer Faculty Fellowship at ORNL),
Prof. Peter Kalu
Industrial/University interest/communication: Dura-Bar, Timken, Southwire, Cryomagnetics, Inc., and Kettering University.

5. **Date Project Initiated:** Initiation Date: October 1, 2001, Current: FY04

6. **Expected Completion Date:** September 30, 2004

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:**

This research and development project is developing a new, high-payoff processing methodology whereby a new class of materials with novel microstructures and superior properties will be achieved in addition to optimizing the current processing of conventional materials.

8. **Technical Barrier(s) Being Addressed:**

A key barrier existed at the initiation of this research effort. Since the use of ultrahigh magnetic field processing for developing customized microstructures and enhanced performance in materials had not been studied before within the United States, experimental facilities did not exist that were robust enough to study the influence of magnetic exposure under controlled isothermal and continuous cooling conditions.

9. **Project Pathway:**

Although this initial technical barrier proved to be a major constraint during the first year of this project, efforts the two subsequent years were focused at developing and utilizing a closed-loop control induction heating system that is LabView software driven and that enables precise magnetic-thermal processing paths to be programmed and executed in an existing ultrahigh magnet system. This new system was used successfully during the latter part of FY'03 and throughout FY'04 to demonstrate the concepts of this new technology approach for materials processing.

10. **Critical Technical Metrics:**

Baseline Metrics:
•Currently no ferrous alloy magnetic processing research is conducted in the United States defining the influence of high magnetic fields on phase stability, phase solubilities, and phase transformation temperatures and kinetics.
•Retained austenite after a quench has to be eliminated either by cryogenic processing or double temper heat treatments.
•Phase transformation temperatures and kinetics can not be modified once alloy chemistry is defined.

Project Metrics:
•The quantitative influence of magnetic field processing on phase stability, phase solubilities, and phase transformation temperatures and kinetics is demonstrated experimentally and predicted thermodynamically for ferromagnetic materials.
•Retained austenite obtained during a quench is reduced via magnetic field processing either during or after the quench.
•The influence of magnetic field processing on phase transformation temperatures and kinetics is documented for several ferrous alloys without modifying their initial chemistry.

PROJECT PLANS AND PROGRESS

11. **Past Accomplishments:**

The results of this research endeavor clearly demonstrate the dramatic influence that magnetic field processing can have on the resulting microstructure in a broad spectrum of *ferromagnetic* alloys. This microstructural influence can be observed as changes in the specific phases that make up the final microstructure, in the relative phase stabilities and volume fractions, in the phase solid solubilities, in the transformation temperatures for both equilibrium and metastable transformation products, in the phase decomposition kinetics for both isothermal and continuous cooling thermal processing conditions, and finally the properties obtained in the resultant microstructures.

The Fe-15Ni alloy results specifically show that the thermodynamics of this alloy system are significantly altered by a magnetic field as evidenced by major changes in the volume fractions and solid solubilities of the α and γ phases at 502°C. The ability to increase the solubility of the substitutional alloying element Ni in the γ phase by ~40% shows the significant promise of magnetic field processing to open new avenues in ferrous metallurgy to develop custom alloys with novel optimized microstructures with enhanced performance. These results support the concept of 3-dimensional phase diagrams which literally adds a new dimension to materials research development. The excellent agreement obtained between the Local Spin Density calculations for Gibbs free energy shift due to a magnetic field and the experimental results for the contribution of the magnetic field to the Gibbs free energy for the Fe-Ni system validates the ability of first principles calculations to predict the observed changes in the temperature-composition-magnetic field space such that modeling endeavors can now drive research efforts to maximize magnetic field processing for a specific alloy family.

Conclusions that can be summarized from the experiments run on the 52100, 1045, and high strength bainitic steel alloys include the following for the effect of magnetic field processing on phase transformation behavior:

-reduces retained austenite in hypereutectoid alloys
-increases transformation temperatures and reduces phase decomposition start times (accelerates kinetics) during continuous cooling
-accelerates austenite decomposition during isothermal transformation
-influences both the equilibrium and metastable phase decomposition transformation sequences.

Two major conclusions of this research are that the transformation temperature shift during continuous cooling due to magnetic field processing is nominally 3°C/T and the contribution of the magnetic field to the Gibbs free energy change for the austenite decomposition transformation in steels is determined to be a shift or ΔG approximately equal to 12.6 J/mol/T.

12. **Future Plans:**

•Definition of Additional Industrial Applications of Magnetic Field Processing (end FY04, in-progress to develop follow-on R&D endeavors with industrial partners for specific applications).

13. **Project Changes:**

A milestone for this endeavor was to develop the capability to determine the material magnetization response data for high magnetic field exposures. Due to the need (based on project budget) to use existing high magnetic field systems with equipment configuration limitations, it was not feasible to incorporate capabilities for measuring these data during actual thermal magnetic processing experiments. Follow-on R&D endeavors will address this issue when capital equipment funding becomes available to procure our own high magnetic field system that can be customized to allow in-situ measurement of these magnetization response data.

14. **Commercialization Potential, Plans, and Activities:**

Industrial companies expressing interest in this technology include Cummins Inc. (ferrous alloys), Caterpillar Inc. (ferrous alloys), Dura-Bar (continuous cast iron), Southwire (power transmission cables), and Timken (ferrous applications). In addition, discussions have been held with a major superconducting magnet manufacturer, Cryomagnetics, Inc., to insure the viability of having commercial magnet systems available in the future for implementation of this technology. One example of an energy savings and cost-reducing application is the elimination of cryogenic treating or double temper heat treatment cycles to eliminate retained austenite in quenched steels. Another significant application is the utilization of magnetic field processing for the reduction of residual stresses in fabricated or in-service components for the purpose of life extension or increased allowable component design stresses.

Once the broad viability of this technology concept has been documented in this Laboratory-led IMF project, future Industry-led collaborations via the IMF Program will be pursued and accomplished for specific industrial applications and commercialization.

15. **Patents, Publications, Presentations:**

2 Patents/Applications:
U.S. Patent Application No. 20040031542: *"Method for Residual Stress Relief and Retained Austenite Destabilization"*, Gerard M. Ludtka, filed on August 13, 2002 (notified 5/2004 that 20 claims have been approved for this patent).

UT-Battelle (ORNL) Invention Disclosure ID 0916, S-96,666: *"Magnetic Field Processing for Customizing Microstructures and Properties in Materials"*, Gerard M. Ludtka, Gail M. Ludtka, Roger A. Kisner, John B. Wilgen, Roger A. Jaramillo, and Don M. Nicholson. Elected for patent preparation and submission.

5 Publications:
Ludtka, G.M., Jaramillo, R.A., Kisner, R.A., Nicholson, D.M., Wilgen, J.B., Mackiewicz-Ludtka, G., Kalu, P.K., "In situ Evidence of Enhanced Transformation Kinetics in a Medium Carbon Steel due to a High Magnetic Field", *Scripta Mater*., **51/2**, 2004, pp 171-174.

Nicholson, D.M., Kisner, R.A., Ludtka, G.M., Sparks, C.J., G., Petit, L., Roger Jaramillo, R.A., G. Mackiewicz-Ludtka, G., Wilgen, J.B., Sheikh-Ali, A., Kalu, P.K., "The Effect of High Magnetic Field on Phase Stability in Fe-Ni", *J. Appl. Physics*, in press (accepted for publication).

Ludtka, G.M., Jaramillo, R.A., Kisner, R.A., Wilgen, J.B., Mackiewicz-Ludtka, G., Nicholson, D.M., Watkins, T.R., Kalu, P.N., England, R.D., "Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance", accepted for publication in the *Proceedings of the International Workshop on Materials Analysis and Processing in Magnetic Fields*, Tallahassee, Florida, March 17-19, 2004 (in press).

Jaramillo, R.A., Babu, S.S., Ludtka, G.M., Kisner, R.A., Wilgen, J.B., Mackiewicz-Ludtka, G., Nicholson, D.M., Kelly, S.M., Murugananth, M., Bhadeshia, H.K.D.H., "Effect of 30 Tesla Magnetic Field on Phase Transformations in a Bainitic High-Strength Steel", submitted to *Scripta Mater*, 2004.

Jaramillo, R.A., Ludtka, G.M., Kisner, R.A., Wilgen, J.B., Mackiewicz-Ludtka, G., Nicholson, D.M., Kalu, P.N., "The Effect of Magnetic Field on the Phase Stability of 52100 Steel", manuscript in preparation for submission to *Metall* & *Mater.Trans.A*, 2004.